# The Evolution of the VASIMR Engine

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**Abstract**. Our future deep space explorers face many daunting challenges but three of these loom high above the rest: Physiological debilitation, radiation sickness and psychological stress. Many counter-measures are presently being considered to ameliorate these difficulties however, in the long run, two important new developments are required: abundant space power and advanced propulsion. The development of the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) addresses these important areas of need. The VASIMR is a high power, radio frequency-driven magnetoplasma rocket, capable of very high exhaust velocities. In addition, its unique architecture allows in-flight mission-optimization of thrust and specific impulse to enhance performance and reduce trip time. A NASA-led, research team, involving industry, academia and government facilities is pursuing the development of this concept in the United States. The technology can be validated, in the near term, in venues such as the International Space Station, where it can also serve as both a drag compensation device and a plasma contactor for the orbital facility. Other near-Earth applications in the commercial and scientific satellite sectors are also envisioned. This presentation covers the present status of the technology, plans for its near term deployment and a vision for its future evolution.

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## INTRODUCTION

Chemical rockets today provide our only means of space transportation; however, their inherent limitations in payload capacity and speed have long been recognized as fundamental impediments to the full-scale human exploration of our solar system. Devices with much higher performance are presently under study at various laboratories. One of these is the Variable Specific Impulse Magnetoplasma Rocket (VASIMR,)[1]. Its genesis dates back to the late 1970s, when a low level effort to define its characteristics began at the Charles Stark Draper Laboratory and the Massachusetts Institute of Technology in Boston. The VASIMR borrows heavily from magnetic fusion technology; however, not being a fusion device, its plasma parameters are substantially relaxed. The early studies in Boston outlined the fundamental physics issues requiring attention and laid the groundwork for the present effort. In 1993, the research was relocated to the Johnson Space Center in Houston, where it has evolved into a strong multilateral activity involving 8 major universities, private industry and two DOE laboratories.

In a fortuitous way, the technologies of the VASIMR and other plasma engines (including ion, pulsed inductive, Hall effect, etc.) are maturing at a time when the International Space Station (ISS) is also becoming a reality. This exciting convergence points to a potential paradigm shift in our plasma rocket test philosophy; namely,

moving life-cycle tests from the conventional Earth-bound vacuum chambers to the more pristine and real environmental conditions which the ISS can now provide. Under this approach, various rocket technologies could be tested side-by-side, in the "ultimate thrust stand." Moreover, besides their intrinsic value as technology demonstrations, these "field tests" would provide a number of significant benefits (and cost savings) to the station itself, including atmospheric drag compensation, effective electrical ionospheric grounding and improvement of the microgravity environment. Such considerations should compel us to undertake a brisk technology development effort in plasma propulsion on the ISS. In this way, the facility could play a key role in enabling rapid interplanetary access in the next decade.

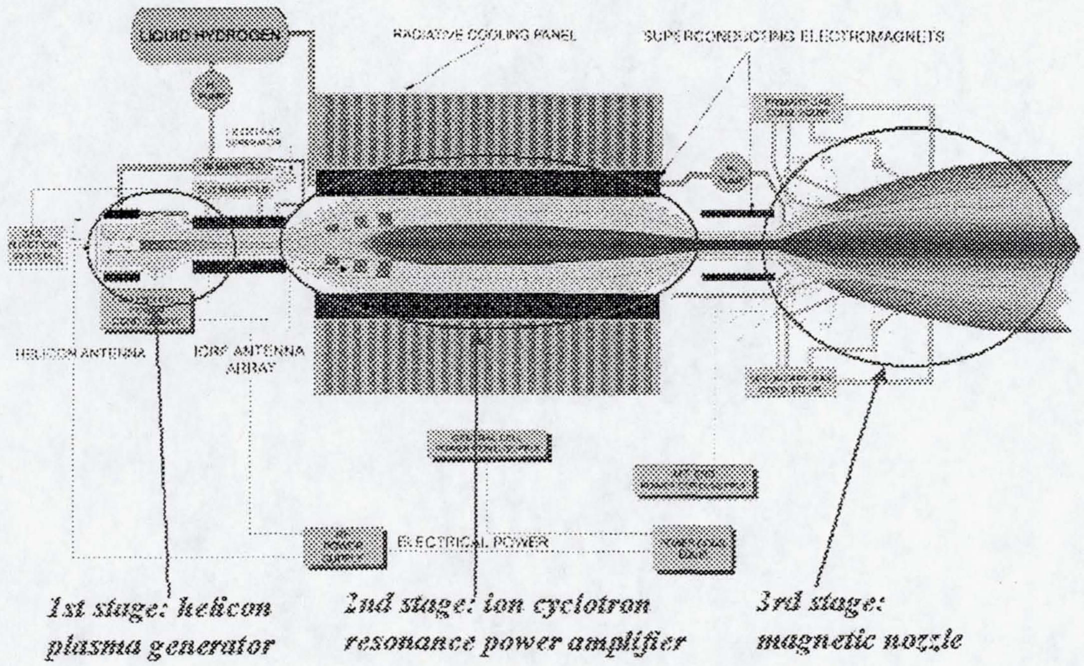
## SYSTEM DESCRIPTION

The VASIMR, shown in Figure 1a., has both, electrothermal and electro-magnetic features. The first of its three stages is a helicon discharge, which produces plasma from feedstock gas by direct radio frequency (RF) electron heating. A second stage further energizes the plasma ions by the process of ion cyclotron resonance heating (ICRH). A magnetic nozzle serves as the third stage, extracting the plasma energy as useful momentum. The system is capable of high power density, as the plasma energy is delivered by wave action, making it electrodeless and less susceptible to component erosion.

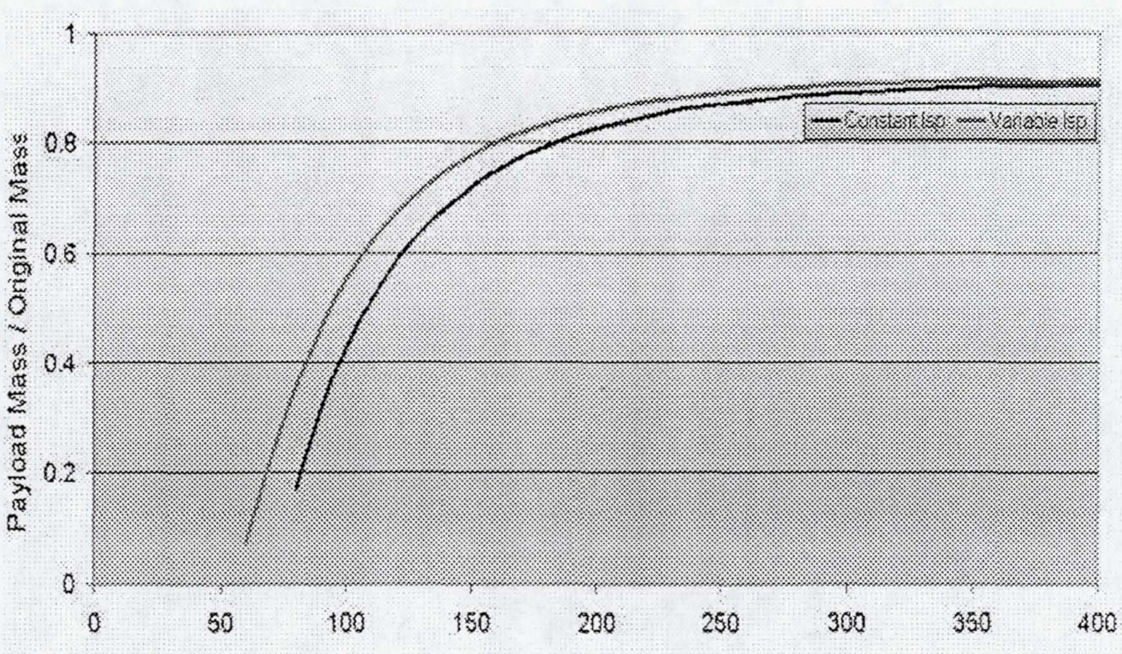
While simpler configurations are being considered for early deployment, the full concept embodies a wide array of important operational features. Chief among these is its capability to vary its exhaust parameters at constant power. This principle, known as constant power throttling (CPT,)[2] optimally tunes the rocket to the conditions of flight. In practice, CPT involves trading off thrust for exhaust velocity (also known as specific impulse, $I_{sp}$.) For short trip times, the variable $I_{sp}$ rocket achieves substantial payload improvement over its constant $I_{sp}$ counterpart, as evidenced by Figure 1b.

The variability of the exhaust comes primarily from power management to both the helicon and ICRH systems. For high thrust, RF is predominantly fed to the helicon, while for high $I_{sp}$ more power is diverted to ICRH with concomitant reductions in thrust. Other methods are being explored, including the use of a magnetic choke at the exhaust cell to keep some of the plasma longer within the power amplification section ($2^{nd}$ stage) and increase its energy content.

For high thrust maneuvers, in a high gravity environment, a plasma "afterburner" could be created by the injection of a hypersonic coaxial neutral gas boundary layer within the nozzle. The gas increases the total mass flow and may recover some of the frozen ionization energy in the form of gas kinetic energy. The presence of the gas also enhances plasma detachment from the magnetic field by collissional diffusion. Investigators from the Princeton Plasma Physics Laboratory and the NASA Marshall Space Flight Center[3,4] are currently studying this process.




(a)

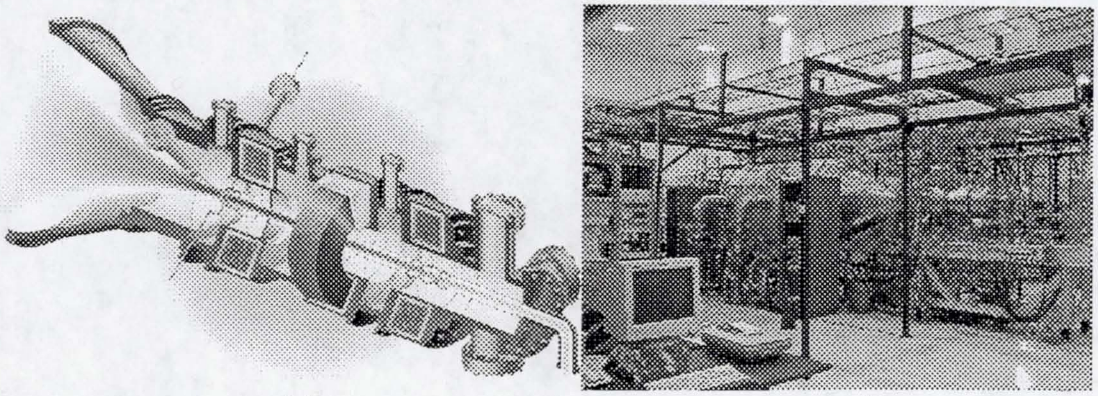



(b)

Fig. 1. Schematic (a) of the VASIMR system and a comparison (b) of constant (lower trace) vs. variable (upper trace) specific impulse for a characteristic one-way high-energy mission to Mars.

# EXPERIMENTAL STUDIES

Experimental research on the VASIMR is being conducted in three complementary experiments in the US. The largest one is the VX-10 device located at the NASA Johnson Space Center in Houston. Two smaller experiments: the Linear Device at The University of Texas at Austin and the Small Radio Frequency Test Facility, known as the "Mini-RFTF", at The Oak Ridge National Laboratory (ORNL) support these investigations. A synoptic view of the VX-10 device is shown in Figure 2(a). A recent photograph and an axial cut of the experiment are shown in Figures 2(b) and 2(c.)



(a) (b)

Figure 2a. Synoptic (a) and actual (b) views of the VX-10 laboratory experiment at the NASA Johnson Space Center.

High density ($>10^{19}/m^{-3}$,) steady-state helicon discharges in hydrogen, helium, deuterium and argon are now routine and, as shown in Figures 3(a) and 3(b,) already show a high velocity exhaust downstream of the magnetic throat. Flow velocities of 15 km/sec, measured with a reciprocating Mach probe, are quite common and indicate a respectably high specific impulse even before ICRH power is added. In the low $I_{sp}$ "helicon only" mode of operation of Figure 3, a Baratron gauge located at the gas injection point measures a rapid total pressure increase. This measurement, shown in Figure 4, is clearly associated with the presence of the plasma and suggests the important thrust contributions of fast neutrals produced by the charge exchange reaction within the helicon tube. Macroscopically, the plasma shows a very well defined shape with no apparent gross instability. A recent photo of a high-density deuterium discharge is shown as an inset in Figure 4.

Under normal conditions, the discharge near the tube exit is well detached from the wall. Sputtering at the upstream injection flange has been eliminated by a high density gas "cushion," which cools the plasma before it can reach the flange. In these discharges, the charge exchange reaction is ubiquitous and probably responsible for some heat loading on the quartz tube wall; however, localized heating observed at various axial locations, may be due mainly to plasma convection by wall-glancing

field lines; further studies to eliminate this effect are ongoing; however, the maximum temperatures observed do not exceed about 500°C.

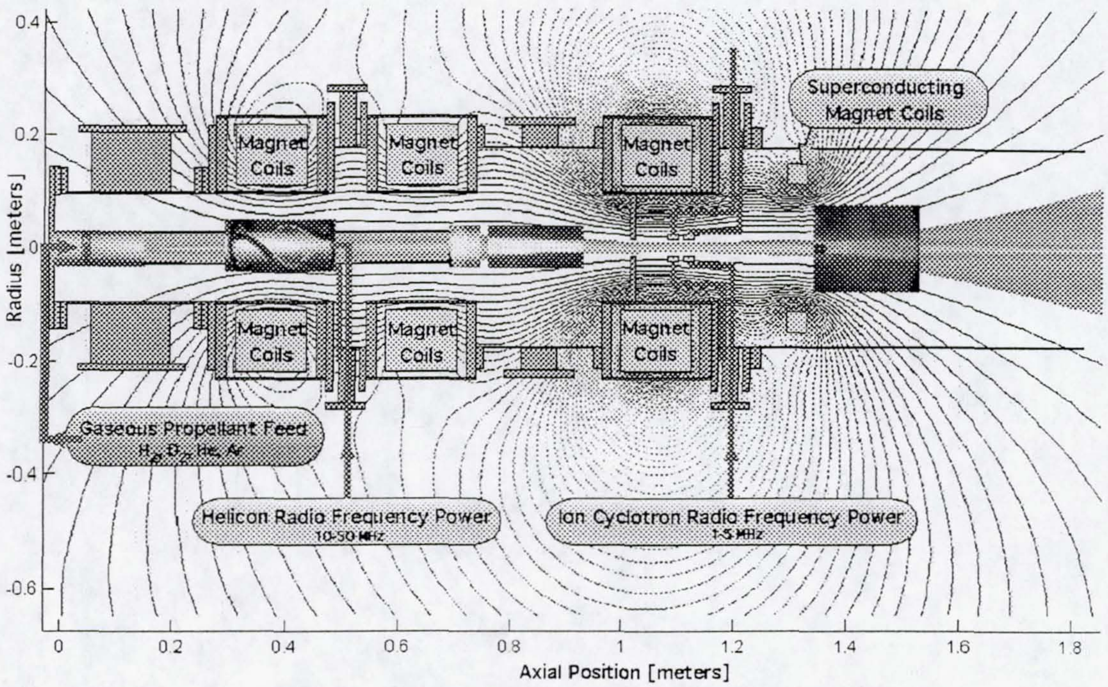



Figure 2c. Axial cut of present VX-10 experiment. A high temperature superconductor is being integrated at the exhaust end to produce a shallow field at the RF resonance.

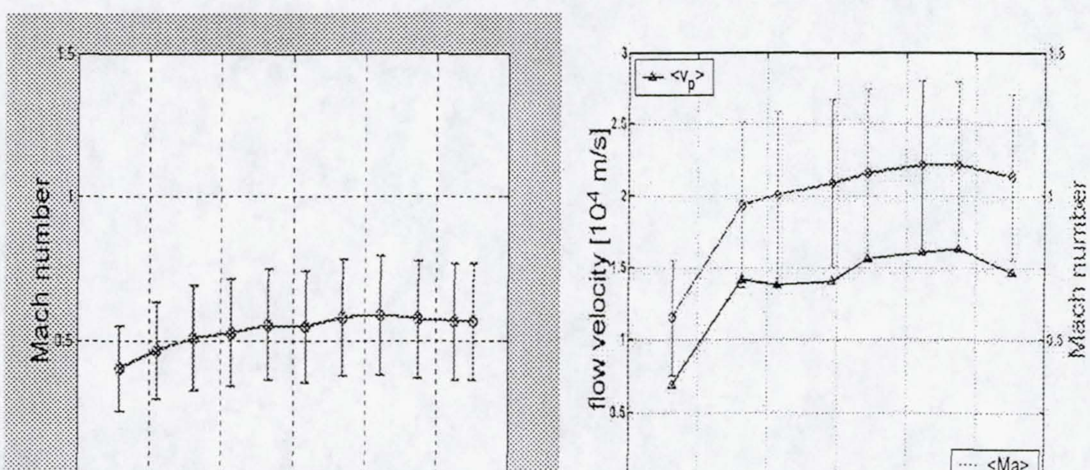



Figure3 shows the Mach number and plasma flow velocity at points upstream (a) and downstream (b) of the magnetic choke.

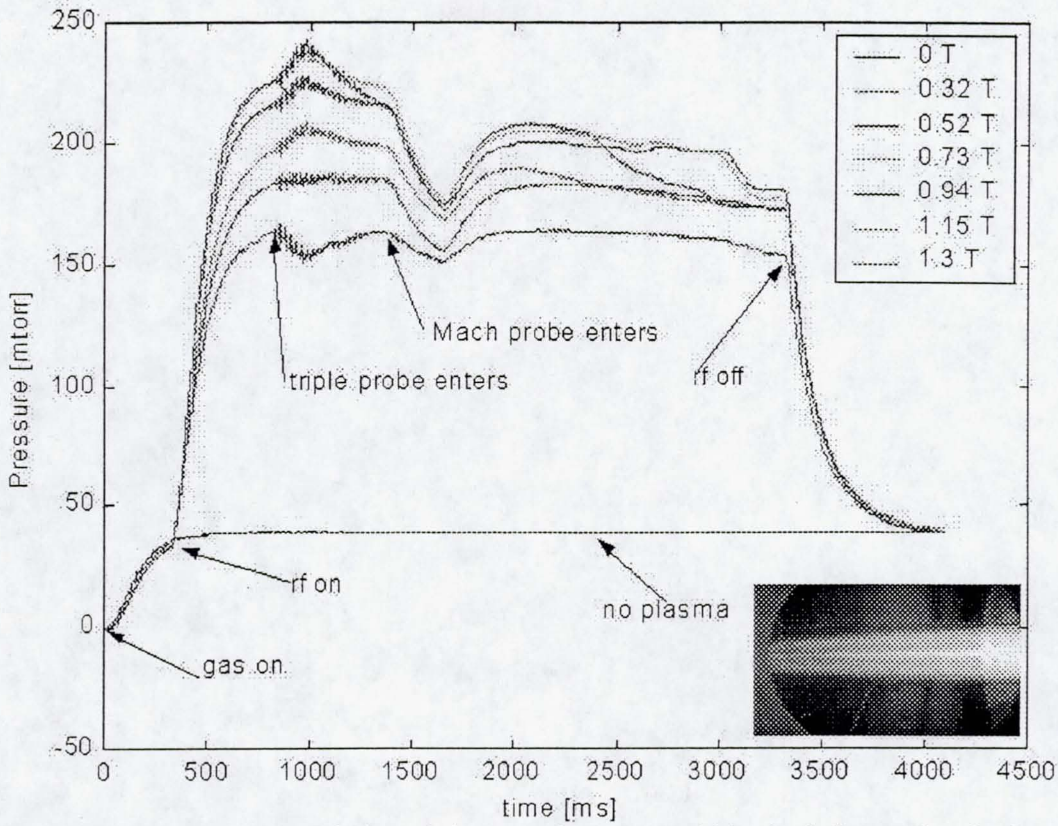



Figure 4 shows the time evolution of the neutral pressure within the helicon tube. A photo of a deuterium discharge is shown as inset.

Recent experiments[5] with gas mixtures (for example,10% hydrogen on helium or deuterium) show the existence of a high-energy minority ion population at velocities greater than 150 km/sec. These measurements have been obtained with two separate retarding potential energy analyzers. The acceleration mechanisms for these high velocities are not fully understood and are the subject of intense study by our research team. However, this intriguing behavior may point to still another "knob" for exhaust variation, namely the control of propellant mixtures.

While the helicon source continues to be optimized, experimental studies of the ICRH stage have now begun. Key components include the RF generators, transmission lines, matching and protection circuits and RF antennas. Two double half-loop antennas are driven with a $90^{\circ}$ phase shift from a single source to achieve the proper ICRH polarization. The system architecture is shown in Figure 5. Total steady-state power capability is 100kW. A critical parameter is the antenna loading or voltage standing wave ratio (VSWR,) a measure of the coupling between the RF power and the plasma as a resistive load. Good coupling depends on maintaining a dense plasma near the antenna, hence our prior emphasis on good helicon performance. Preliminary loading measurements show this strategy paying off, as ICRH loading continues to improve. As of this writing, a VSWR of 2 has been measured, implying that at least half of the incoming RF power is being coupled to the plasma.

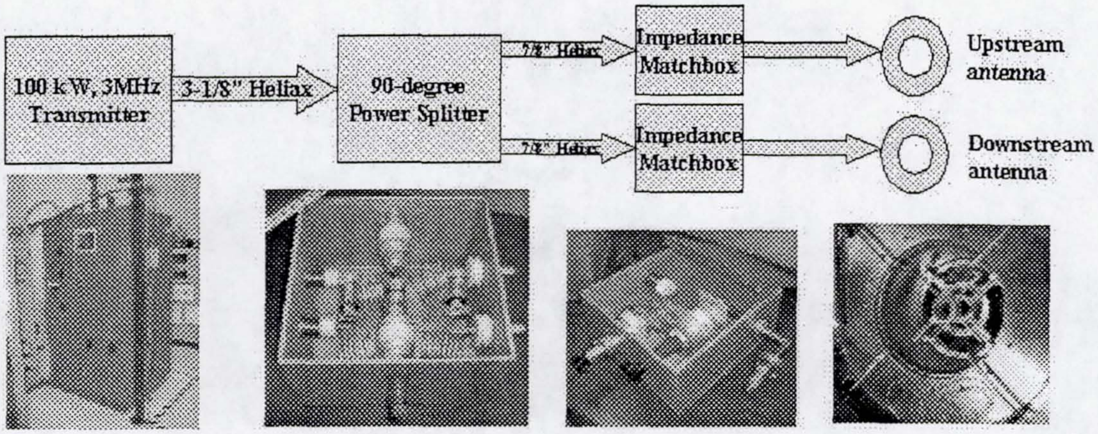



Fig. 5. Ion cyclotron resonance system architecture

## THEORETICAL STUDIES

Many important aspects of VASIMR physics are being addressed in complementary theoretical studies and simulations. A particularly interesting mechanism, which we refer to as the Alfven transition is responsible for the plasma detachment from the ship's magnetic field after the expansion is complete. This issue has been addressed by R. Sagdeev[6], of the University of Maryland and B. Breizman[7] of the University of Texas at Austin. As the plasma accelerates in the magnetic nozzle, its speed reaches the Alfven speed (a characteristic speed at which pressure disturbances propagate along the magnetic field.) This point defines a boundary, beyond which the dynamics of the flow downstream have no effect on the upstream parameters. The plasma detaches, carrying with it a small amount of the field. The energy expenditure in this field distortion poses only a minor tax on the performance of the rocket. Our studies show that, with properly designed nozzles, the plasma detaches from the rocket at distances of 1-2 m from the magnetic throat. In a magnetic nozzle, the Alfven speed plays a similar role as the sonic speed in a conventional nozzle.

## ENGINEERING AND TECHNOLOGY DEVELOPMENT

Important engineering aspects are being considered in concert with the development of the physics. For example, the utilization of cryogenic propellants such as hydrogen and helium will favor regenerative thermal designs. Advanced heat pipes, high temperature superconductors and new solid-state RF amplifiers are some of the new technologies being developed. Early space testing of these and other electric propulsion technologies is sought. Furthermore, in exploring the above-mentioned relevance to the International Space Station, an experimental VASIMR operating at 25kW could provide sufficient thrust to neutralize the atmospheric drag on the facility. The system could operate on deuterium or hydrogen. The later one could be scavenged

from the present ISS life support system, where it is treated as waste, producing an extra savings in propellant transportation. A preliminary conceptual design for such a space experiment is shown in Figure 6. The device will operate at an estimated efficiency of .5 and produce .5 N of thrust at a specific impulse of 5400 sec.

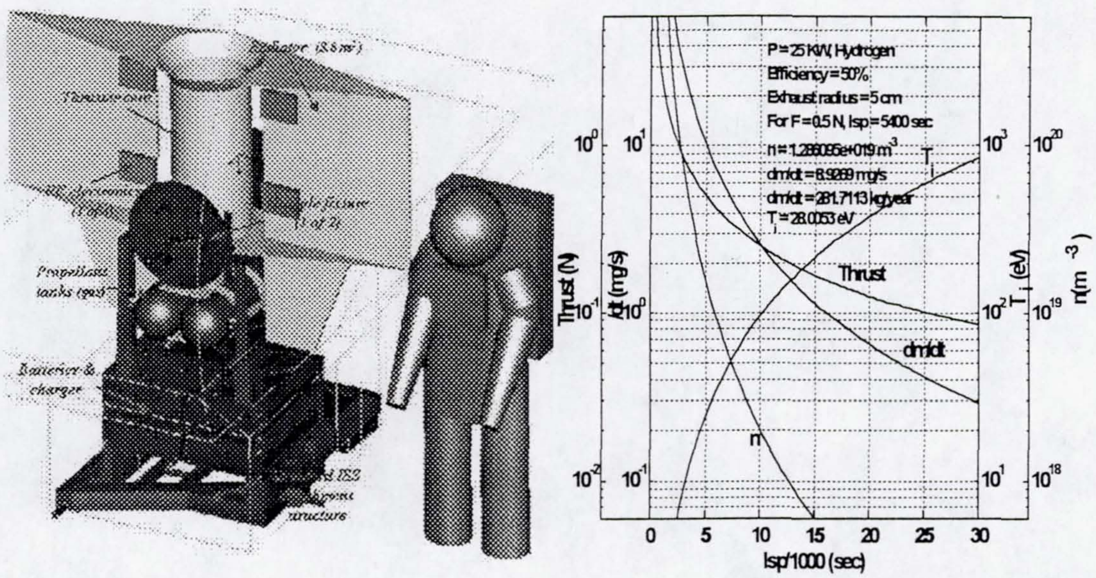
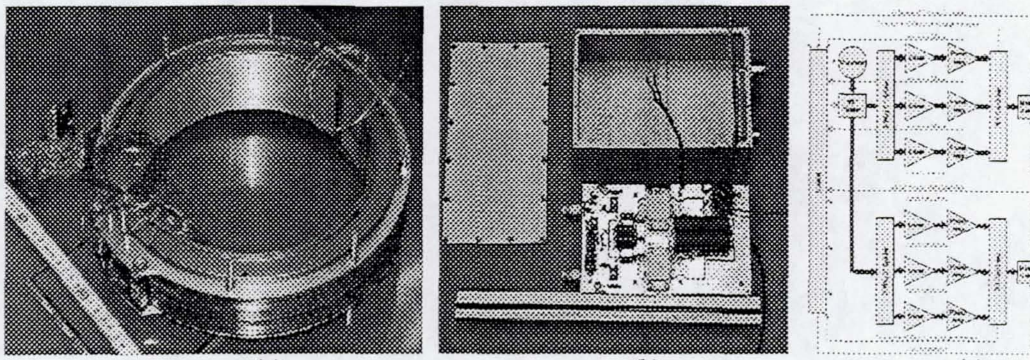



Fig. 6. Conceptual design (a) of the first VASIMR space experiment for the International Space Station. The performance envelope (b) shows propulsion parameters as functions of the specific impulse.

Taking advantage of the space environment, the VASIMR uses high temperature superconductors to produce its required magnetic field. On the ISS, thermal control of the experiment will involve combining radiation cooling and proper shielding. A small amount of supplemental heat rejection in the form of a cryocooler may also be needed. Advanced designs using cryogenic propellant storage could also provide regenerative cooling by the propellant itself.

At present, lightweight superconductors based on Bismuth Strontium Calcium Copper Oxide (BSCCO) compounds have already reduced the magnet weight by more than one order of magnitude. Continuing advances in this technology bode well for even lighter designs. The first flight-like VASIMR BSCCO magnet, shown in Figure 7a, is being integrated into the existing VX-10 experiment to replace one of the conventional copper magnets. At only 5kg (as compared with the 150kg unit it is replacing), it produces a .28 Tesla field on axis at a temperature of 40°K.

Miniaturization of the RF equipment is another important goal. To this end, the research team has been working with high-power, solid-state transistor technology to achieve suitable lightweight amplifier designs. Two 1 kW RF modules such as the one on Figure 7b have been built and are being evaluated. Clusters of these units are being considered as the building blocks for both the helicon and ICR systems. The architecture will be based on robustness and reliability.



(a) (b) (c)

Fig. 7. The high temperature BSCCO superconducting magnet (a) will be integrated in the VX-10 device downstream of the ICRH section. A solid state 1 kW RF amplifier (b) has been developed as the building block of the RF system. Integrated in clusters (c) they can provide robustness and reliability.

## MISSION APPLICATIONS

Operationally, exhaust modulation can have profound implications to rocket propulsion. For example, the high thrust mode of the VASIMR can be employed in the early stages of orbital boost in a high gravity environment. As the vehicle escapes the gravitational pull, its exhaust would gradually transition to a high $I_{sp}$ mode, and continue to accelerate the craft to its full cruise speed. The process would reverse itself as the ship approaches the high gravity environment of its destination. For planetary fly-by, or deep space missions not requiring orbital insertion, the spacecraft engine would be capable of better matching the exhaust velocity to the vehicle velocity for optimum propulsive efficiency. Other benefits pertaining to orbital operations are also envisioned. These include efficient round-trip capability to the high-energy orbits of commercial interest in the Earth-Moon environment, as well as rapid and economical satellite maintenance, repair and refueling.

For human exploration, VASIMR technology enables very fast human planetary transits to Mars and beyond. The reduction in trip time results in reduced exposure to radiation and microgravity, thus reducing the crew's physiological de-conditioning. Moreover, the utilization of liquid hydrogen propellant will provide an effective radiation shield. A conceptual architecture for a 115-day mission to Mars is shown in Figure 11. Three fission reactors with a total power level of 12 MW would power the spacecraft. Such power-rich architectures are essential for human survival, as they enable abort capability in the event of unforeseen contingencies.

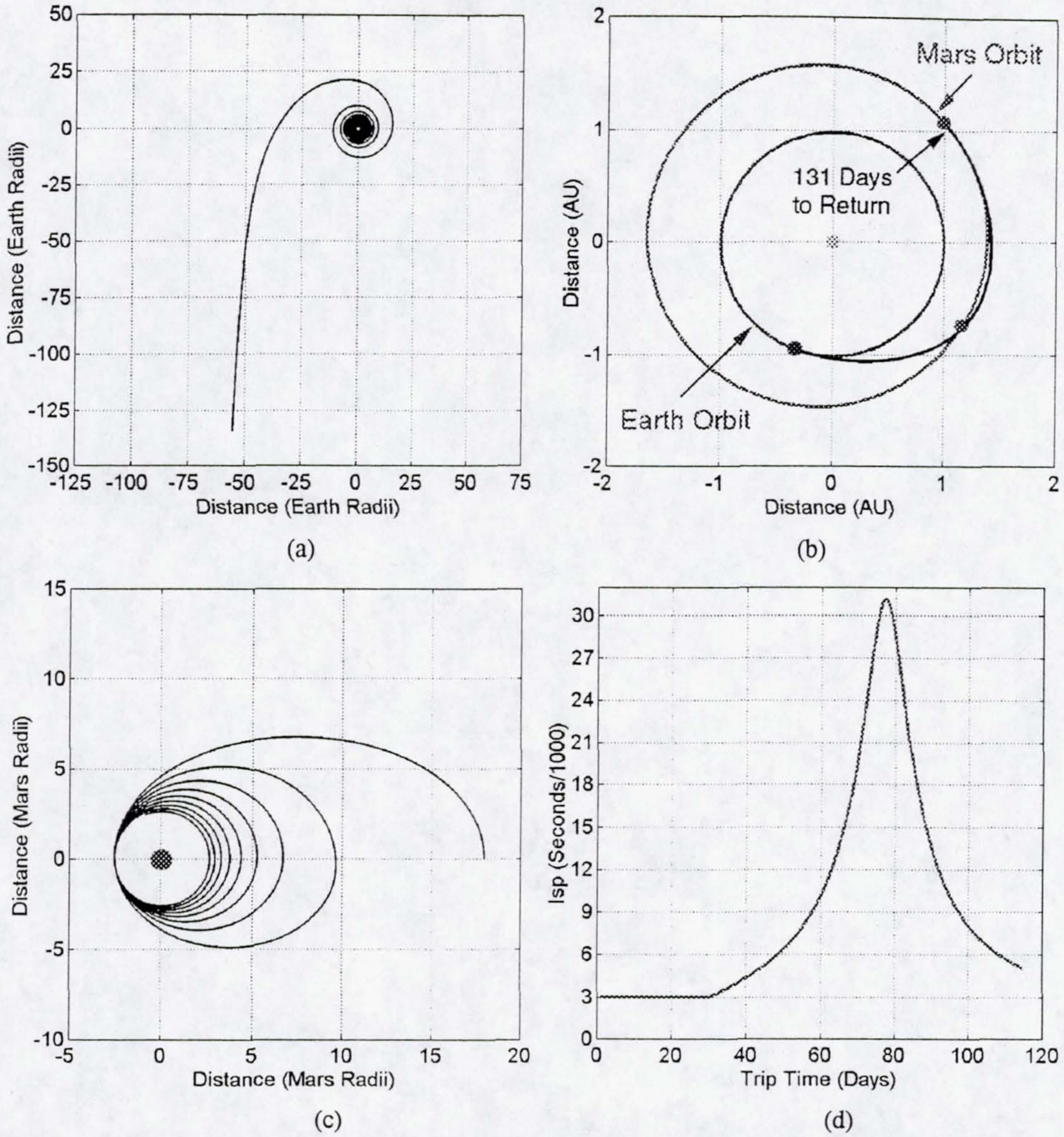



Fig. 11. VASIMR human Mars mission. The 188 mT piloted ship departs Earth orbit and climbs on a 30-day spiral (a) followed by a heliocentric trajectory to two Mars encounters at 85 and 216 days respectively (b). The crew lands on the first encounter, while the mother ship continues on to the second encounter and gradually spirals into low Mars orbit (c) to await the completion of the surface mission. The $I_{sp}$ schedule (d) delivers the craft for aerobraking at Mars at a relative velocity of 6.8 km/sec.

## MAPPING A PATH TO THE FUTURE

The development of the VASIMR and other advanced plasma rockets addresses a fundamental need in space transportation. Such an investment in technology will also benefit the commercial satellite industry, by enabling much higher payloads and mission flexibility. While a relative newcomer to the family of advanced rockets, VASIMR has evolved rapidly and its research team is now demonstrating important

results in several areas. Such advances place it in a competitive realm with the more mature technologies of electrostatic plasma accelerators.

Without diminishing the value of ground-based experiments, the reality of the International Space Station provides today a new and unique laboratory for testing these technologies and accelerating their development. Since the infrastructure needs (electrical power, propellant flow control, diagnostics, command and data acquisition, etc.) of most electric propulsion concepts are similar, such a platform would allow the testing of multiple concepts side-by-side and provide the ultimate "thrust stand" to evaluate performance. Moreover, in addition to its intrinsic value, if installed at the correct location, the platform would provide drag compensation for the orbital complex and a host of other benefits as well. These considerations could also imply that a significant amount of commercial value may be found in the operation of such a facility. An early VASIMR experiment on the space station is being formulated not just to demonstrate the feasibility of the VASIMR concept, but the generic usefulness of such a test platform as well.

For the future, returning to its magnetic fusion roots, VASIMR could be viewed as a precursor to fusion rockets, where the requirements of plasma density and temperature are greatly increased. Whether fusion rockets will ever become a reality is not yet clear, but the tantalizing possibilities are nevertheless being examined. As an ignited fusion rocket or as a high power fission-electric one, the present VASIMR development provides an evolutionary path, with exciting and immediate applications en-route. Our future generations will use these systems for rapid access to the solar system and ultimately the stars. We now find ourselves preparing the groundwork for their eventual success.

## ACKNOWLEDGEMENTS

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